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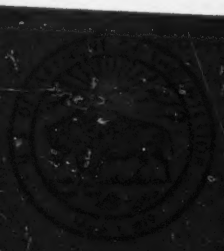

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THE COMPONENTS OF OXYGENATION IN FLOWING STREAMS

by

Francis S. Stay, Jr.,
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Billy L. DePrater,
and Jack W. Keeley

Research Program
Robert S. Kerr Water Research Center
Ada, Oklahoma

U. S. DEPARTMENT OF THE INTERIOR
Federal Water Pollution Control Administration

April 1967

ABSTRACT

It is the intent of this report to present a method which can be used to separate and measure the components of reaeration in flowing waters. Plastic chambers are used to separate the effects of photosynthesis, diffusion, and respiration on the oxygen balance of a stream's regimen and further separate these parameters according to the benthos and organisms which are free-floating.

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THE COMPONENTS OF OXYGENATION IN FLOWING STREAMS

by

Francis S. Stay, Jr., William R. Duffer, Billy L. DePrater, and Jack W. Keeley*

INTRODUCTION

The theory of waste assimilation in flowing streams has long been understood and, in a few cases, the application of theory has been made. The classic equations of Streeter and Phelps were applied to the Ohio River with considerable success; however, the adaptability of theory to streams in the southwestern United States has been neglected.

A basic need in this field lies in the understanding of the behavior of the various components of reaeration and how these differ according to stream type and prevailing climatological conditions.

It is the intent of this work to present a method and describe apparatus--the use of which will allow the components of reaeration to be evaluated separately in flowing streams. In addition, some data are presented demonstrating the type of information that can be gleaned from the use of this apparatus and procedure. Future studies will employ this method for measuring the parameters of oxygenation in more detail.

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In order to understand the kinetics involved in stabilizing discharged wastes and the corresponding effect of this stabilization on stream quality, it is necessary to have an understanding of the parameters (and their interrelationship) involved in the natural oxygen balance of streams. Further, it is important to know what part of the available oxygen can be depended upon for waste stabilization and what part is possibly lost by diffusion or to the stream's oxygen demand.

The basic instream oxygen balance is dependent upon a number of factors. Among these, Edwards and Owens[1] list photosynthesis as an additive parameter; respiration by plants, animals, and aerobic bacteria as an oxygen demand; and diffusion as a supply or demand parameter dependent upon the concentration of dissolved oxygen in relation to saturation.

Oxygen produced in photosynthesis results when carbohydrates are synthesized from carbon dioxide and water by aquatic plants, in this case. Reduction by photosynthesis requires radiant energy, and its magnitude depends upon the extent of penetration in the aquatic environment. This production is necessarily diurnal in nature with a maximum during the afternoon and being reduced to zero or near zero at night. In summer when the saturation values of oxygen are low, and sunlight is intense, oxygen is often lost by diffusion to the atmosphere.

The diffusion of oxygen is dependent on the rate of change of the liquid-gas interface. It follows then that cascading waters

would absorb oxygen faster than those which are quiescent. By the same token, diffusion can cause a loss in dissolved oxygen if the water is in a supersaturated state.

Aerobic respiration is defined as the use of oxygen for the oxidation of carbohydrates in the living cell with the resulting release of energy and carbon dioxide. This phenomena results in an oxygen demand on the stream's regimen, and its magnitude is primarily dependent on the established biotic population.

Traditionally, engineers have estimated stream reaeration rates largely on the basis of stream type; for example, sluggish, large slow, large normal, and swift. Although these estimates are often all that is available, they can lead to significant errors in the determination of the effects of discharged wastes on stream quality.

Several formulations have been proposed relating reaeration rates to such parameters as the molecular diffusion coefficient, Manning's roughness coefficient, mean depth, wetted parameter, and velocity.[2,3,4,5] Although there exists a significant correlation between these calculations and what are reported to be "observed" observations, the standard error is often large enough to make the confidence of using such values low. In addition, many of these predictive techniques negate the production of oxygen by photosynthesis and deal only with reaeration by diffusion.

Field studies to determine reaeration rates are often misleading in that the natural system is altered or the components diffusion, respiration, and photosynthesis are not separated. Indeed, there exists a considerable difference in opinion concerning the relative contributions of oxygen between photosynthesis and diffusion and the reliability of each in waste stabilization.[6]

Hull[7,8] and others have demonstrated, in many instances, the value of photosynthesis as a source of dependable oxygen in streams and reservoirs.

It appears that, in reality, the two cannot be separated in that when oxygen production by algae is high, the diffusion of oxygen becomes lower and, in fact, becomes negative, resulting in loss of oxygen when the stream exceeds saturation. On the other hand, at night and when radiant energy from the sun is low, most reaeration is attributed to diffusion.

Curiously, the engineer, while estimating the effects of photosynthesis, is preoccupied with diffusion, while the biologist labors in a converse manner. The engineer usually ignores the natural respiration of the stream's established biological population, while the biologist estimates it based on diurnal oxygen observations.

The light-dark bottle method of differentiating between photosynthesis and respiration changes conditions by introducing an unnaturally high surface-to-volume ratio to the sample of water being studied. In addition, quiescence imparted to the

sample by using bottles affects the natural flow of food to and of waste products from the trapped organisms. It is of particular importance to note that, when using the light-dark bottle technique in flowing streams, both oxygen production and respiration of the benthos is negated. Many streams in the Southwest are of such depth and clarity that photosynthetic productivity in the benthos is in great excess to that which is free-floating in the stream.(9) It would appear that the use of the light-dark method is more practical in reservoir work than in streams.

Diurnal oxygen studies(10) are useful in that respiration can be estimated by the rate of oxygen decrease after sunset, and net production by photosynthesis can be calculated by correcting the oxygen content measured during the day. This requires estimating respiration and diffusion.

The light-dark bottle technique and diurnal studies share one common aspect--in both cases, it is necessary to estimate the diffusion parameter. Copeland and Duffer(11) attempted to reconcile this problem by use of a plastic dome which was allowed to float on the water surface and from which a difference in trapped oxygen within the dome was measured as a base for diffusion calculations. This work required daytime diffusion rates to be estimated on the basis of diffusion measurements made at night. In addition, the method was handicapped by being affected by antecedent flow conditions.

Several methods have been proposed[1,5,12] to take into account the effects of antecedent flow conditions by appropriate tracer techniques. This work has been extended with some success to correlate mixing phenomena with reaeration characteristics, particularly of a diffusion nature.

Symons[13] eliminated many of the problems having to do with measuring and separating the components of oxygenation by introducing plastic chambers with automated oxygen probes. These chambers were stirred and were large enough to reduce the surface-to-volume ratio. One chamber was clear and closed to the atmosphere, one was black and closed to the atmosphere, and the other was clear and open to the atmosphere. With this arrangement, it became possible to measure by difference, photosynthesis, diffusion, and respiration. Although in this work there was no satisfactory manner by which photosynthesis and respiration attributed to the benthos could be measured, its intent was for use in reservoir work where depths were great enough to negate sunlight reaching the benthos.

Thomas and O'Connell[14] used small plastic chambers automated to measure dissolved oxygen in a manner similar to that of Symons. The difference here was that an artificial benthos was introduced by using algae found in the stream. This growth was removed from the stream bottom, placed in petri dishes, and after 24 hours was attached to baffles within the plastic chambers. By removing and, thereby, selecting the biological population from the stream, the organisms are possibly damaged and unrepresentative.

METHODOLOGY

The components of the oxygen balance in flowing streams can be measured separately with a minimum disturbance to the physical system and the biological population by using three plastic chambers; one chamber clear and closed to the atmosphere, one chamber black and closed to the atmosphere, and the third chamber clear and open to the atmosphere. The chambers are bolted to artificial substrates, constructed to represent, physically, the type of stream bottom that actually exists. The substrates are allowed to stabilize for at least six weeks.

Each chamber is equipped with paddles which create a bottom velocity in the same direction and of the same magnitude which naturally occurs at the point of study. The chambers are equipped with apparatus by which the gases leaving solution can be measured and analyzed for oxygen content. These volumes of gases are adjusted to standard temperature and pressure conditions. On this basis, the weight of oxygen is determined.

Conditions in the black chamber represent an oxygen demand due to respiration only, because it is closed to the atmosphere eliminating diffusion, and it does not allow sunlight for photosynthesis.

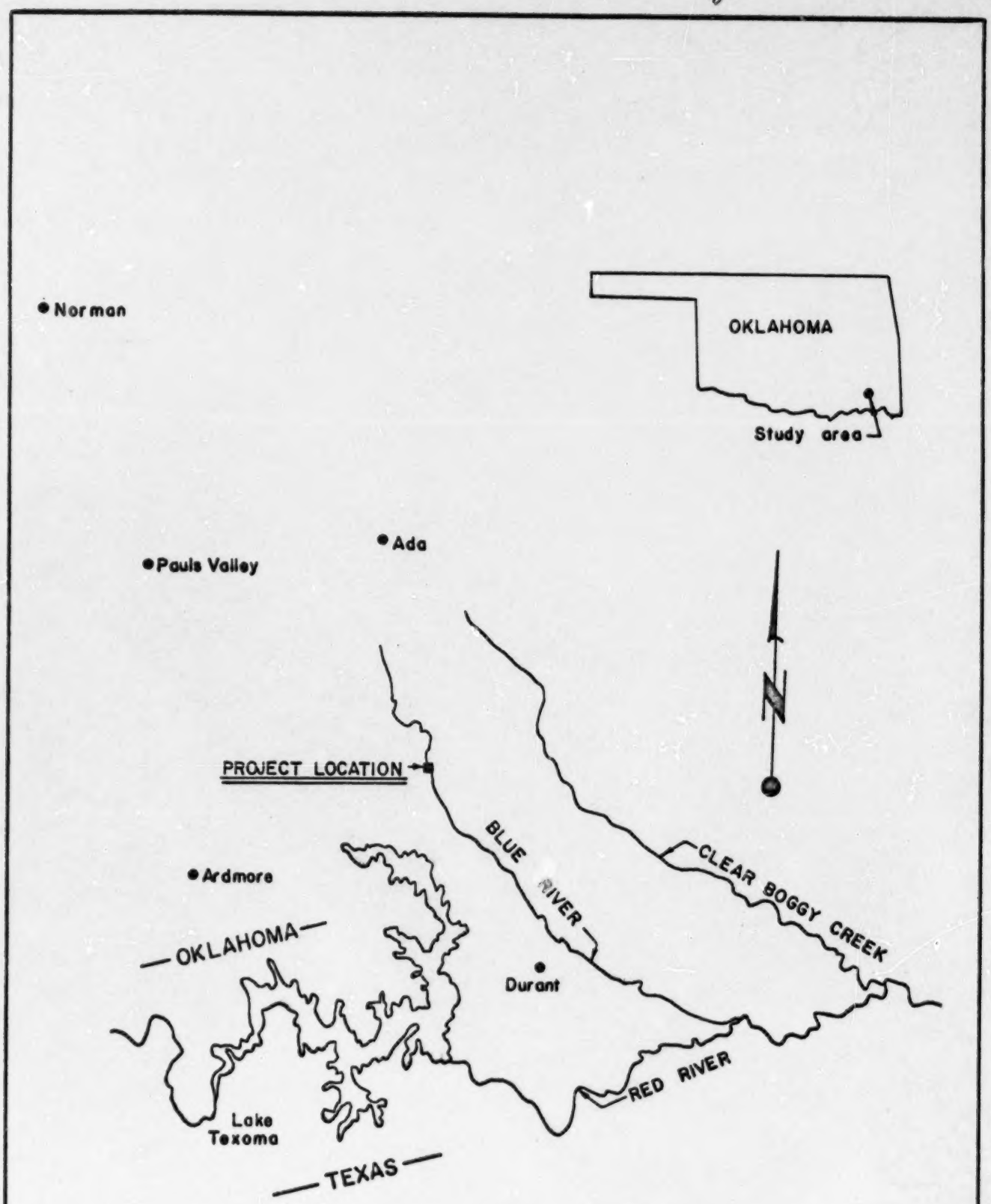
The oxygen concentration in the clear chamber is affected by respiration and photosynthesis but not diffusion because it is also closed to the atmosphere. The difference in oxygen production between the clear and black chambers is the amount of oxygen produced by photosynthesis.

Conditions in the clear chamber, which is open to the atmosphere, represents photosynthesis, diffusion, and respiration. At the same time, errors which may be accompanied by a lack of knowledge of antecedent flow conditions are eliminated. The difference in oxygen production between the clear chamber and the open chamber is that amount of oxygen introduced to or lost from the system by diffusion.

Additional information is gained by the introduction of a plastic plate between the benthos and that part of the stream trapped in the plastic chambers. By making the measurements mentioned above, it is then possible to determine that portion of the oxygen balance due to the benthic population and that due to free-floating organisms.

Dissolved oxygen measurements were made in conjunction with supporting information such as atmospheric pressure, temperature, stream velocity profile, light intensity, and the percent of light transmittance to the benthos. Each test run is made on a diurnal basis with the chambers open to the benthos for about 24 hours and then closed to the benthos for another 24 hours.

The Blue River, located in south central Oklahoma, was selected as a test site for this investigation (Figure 1). A 1300-foot section of this river was selected because it encompasses various types of stream conditions ranging from sections with high velocities and granite bottoms to low velocity and sand bottom.



COMPONENTS OF
OXYGENATION IN FLOWING STREAMS
BLUE RIVER – OKLAHOMA

LOCATION MAP

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FIGURE 1

Table 1 presents typical physical, chemical, and biological characteristics of the Blue River at the test site.

Table 1

Average Characteristics of the Blue River at the Test Location[9,11,16]

Width	52 ft (15.8m)	Turbidity (mg/1)	12
Depth	1.4 ft (0.42m)	pH	8.3
Velocity	0.7 ft/sec (0.21m/sec)	Specific Conductance (μmhos/cm)	530
Discharge	48 ft^3/sec (1.35m^3/sec)	Alkalinity (mg/1)	
		bicarbonate	286
Temperature Range ^oC		carbonate	12
Spring	18-26		
Summer	23-31	Suspended Organic Residue (g/m^2)	41
Fall	9-15	Benthic Organic Matter (g/m^2)	212
Winter	7-16	Suspended Chlorophyll a (g/m^2)	0.004
		Benthic Chlorophyll a (g/m^2)	0.39

Blue River, in the area of study, is fed mostly by springs and maintains a fairly constant flow during the summer months.

Two locations were selected for initial tests, and three artificial substrates were placed at each site and allowed to stabilize for about 12 weeks. Both locations had depths of about 2 feet (0.61m). Differences in the two locations were, for Runs 1 and 2 the velocity was about 1.6 ft/ sec (0.49m/sec) with a granite substrate, while Run 3 was in an area of sand deposition where the velocity was near zero.

Runs 1 and 2 were run at the same location with data being collected on each for about 24 hours. Run 1 was made with the

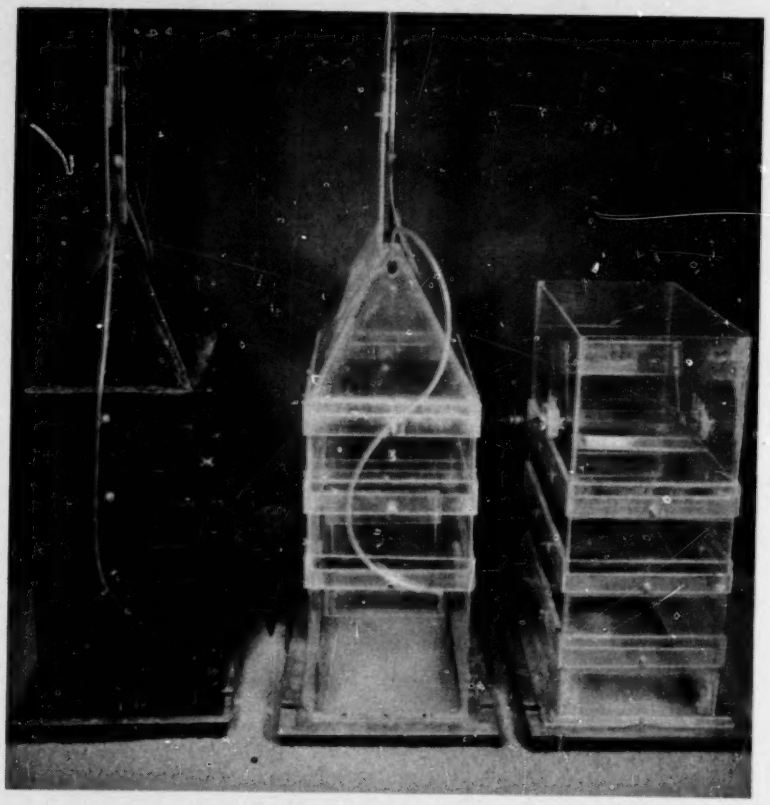
chamber open to the benthos, while during Run 2 a plastic plate separated each chamber from the benthos.

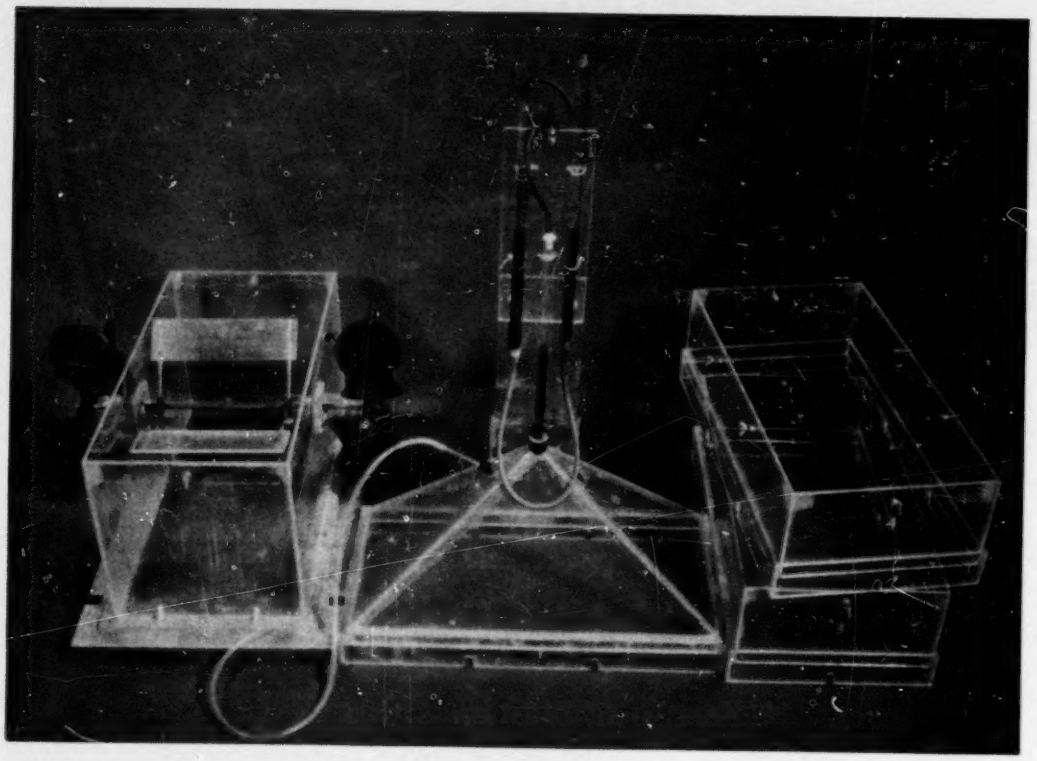
Run 3 was carried out over a period of about 48 hours during which time the chambers were always open to the benthos. Limited sunlight was experienced during the first 24 hours followed by a 24-hour period of maximum sunlight.

A description of the apparatus used in these investigations follows:

Stream Oxygen Chambers

There are three chambers made of one-quarter inch plexiglass. Two of these are clear, while the other is black (Figure 2). One clear chamber is open to the atmosphere, while the other two chambers have pyramidal tops to trap gases and close the chambers to the atmosphere. All three chambers are 12" wide, 24" long, and the height can be varied from 24" to 42" with 6" segments. The volume of these chambers is such that at minimum heights, the surface-to-volume ratio is not high enough to cause a significant increase in the number of organisms in the chamber over that which exists in the stream. Each of the three chambers has a foam rubber collar on the bottom which makes a tight connection when attached to the artificial substrate. The two chambers with pyramidal-shaped tops are equipped with manometers at the apex to collect any gases leaving solution. Also, located in this top is a sample extraction tube for the removal of water samples and a dissolved oxygen probe and agitator. A 3-blade paddle wheel is used to





NOT REPRODUCIBLE

COMPONENTS OF
OXYGENATION IN FLOWING STREAMS
BLUE RIVER - OKLAHOMA

PLASTIC CHAMBERS

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FIGURE 2

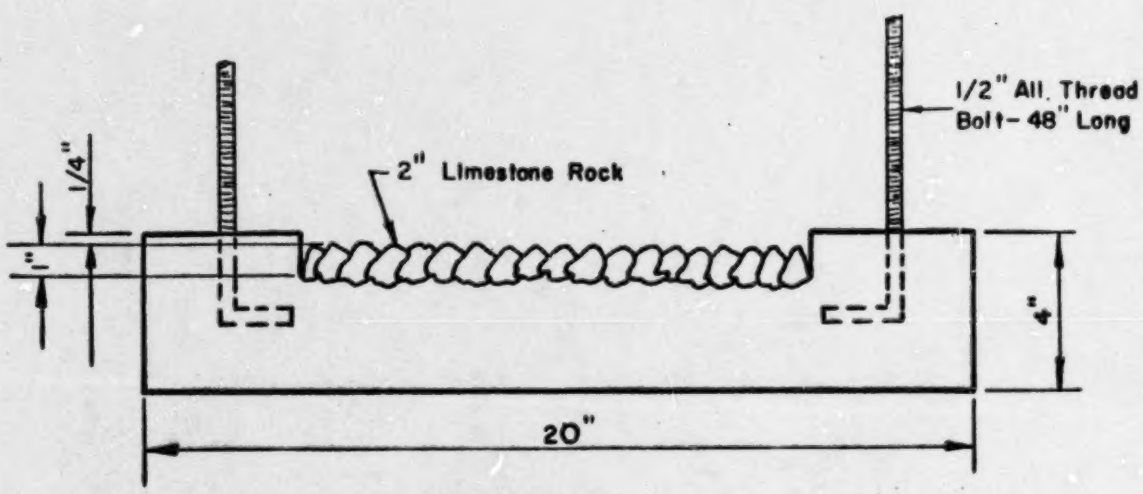
produce a current which carries waste products away from and food to the organisms in the chamber. The paddle wheel can be powered either by a set of cups mounted to the ends of the paddle wheel shaft or by a 6-volt D.C. motor and gear reduction unit mounted on a platform above the water. When using cups to power the paddle wheel, the current produced in the chamber will be similar in magnitude to that driving the cups. When the D.C. motor is used to power the paddle wheel, the current in the chamber is made to approximate that in the stream by the use of an appropriate gear reduction ratio.

Artificial Substrate

The substrate is a 32"x20"x4" concrete slab with a 1 1/4"x24"x12" indentation in the center. Two-inch diameter limestone rocks project approximately 1" from the concrete of the indentation. These rocks simulate the bottom type of the stream section being studied. In addition, the bottom type of the artificial substrate can be changed by filling the indentation with the appropriate material. At the location for Run 3, the indentation had filled with sand by deposition. As shown in Figure 3, four, 48" threaded, 1/2" bars are anchored in the concrete slab. These bars enable the chambers to be secured without bringing the substrate to the surface and possibly altering the benthic population.

Dissolved Oxygen Analyzer and Recorder

Membrane-type oxygen analyzers were used in this study. Agitators were used to provide a constant changing of the sample past the probe.



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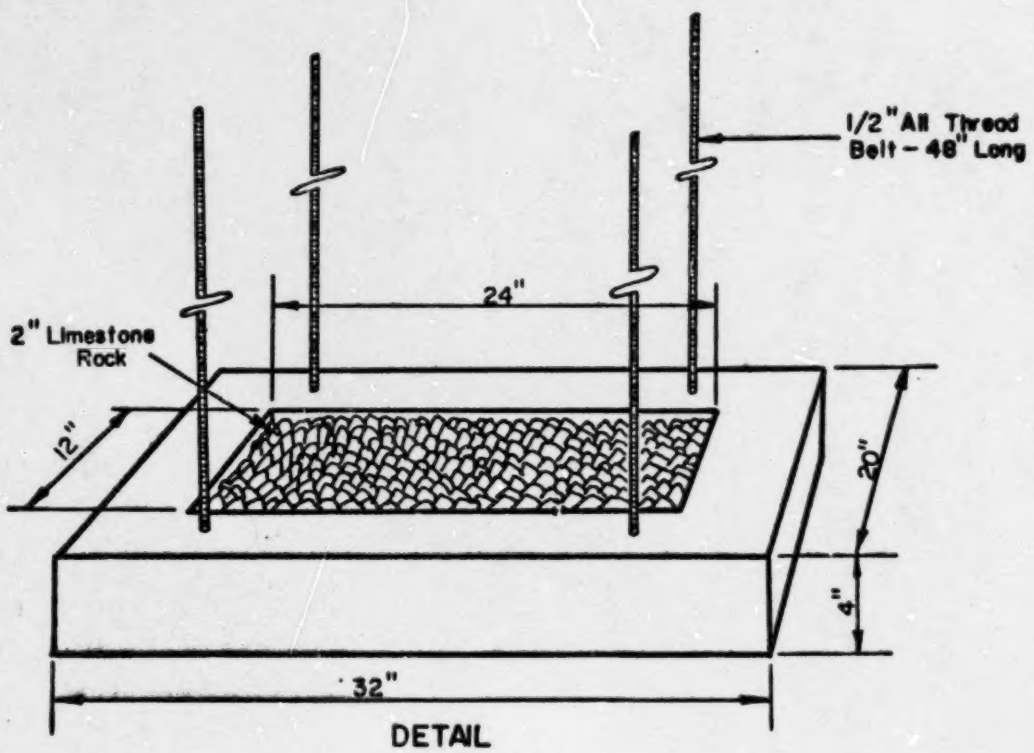

DETAIL

COMPONENTS OF
OXYGENATION IN FLOWING STREAMS
BLUE RIVER - OKLAHOMA

ARTIFICIAL SUBSTRATE

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FIGURE 3

In an attempt to obtain a continuous D.O. sample through the test period, the three D.O. analyzers were connected to a single-channel recorder on a shared-time basis. It was found that the results obtained, as measured against the Winkler method, were only satisfactory for about 20 continuous hours without changing membranes.

Oxygen Gas Analyzer

A modification of the Scholander Gas Analyzer for field analysis of percent O_2 collected in the manometer was used in the latter part of this study.[15] This apparatus uses a pyrogallol solution as an oxygen absorbent and is accurate to 1 percent of total volume analyzed.

Photometers

A submarine photometer was used for comparative measurement of light at the water surface and the substrate surface.

A light meter, calibrated in foot-candles, was used to measure light intensities at the water surface throughout the test period.

PRESENTATION OF DATA

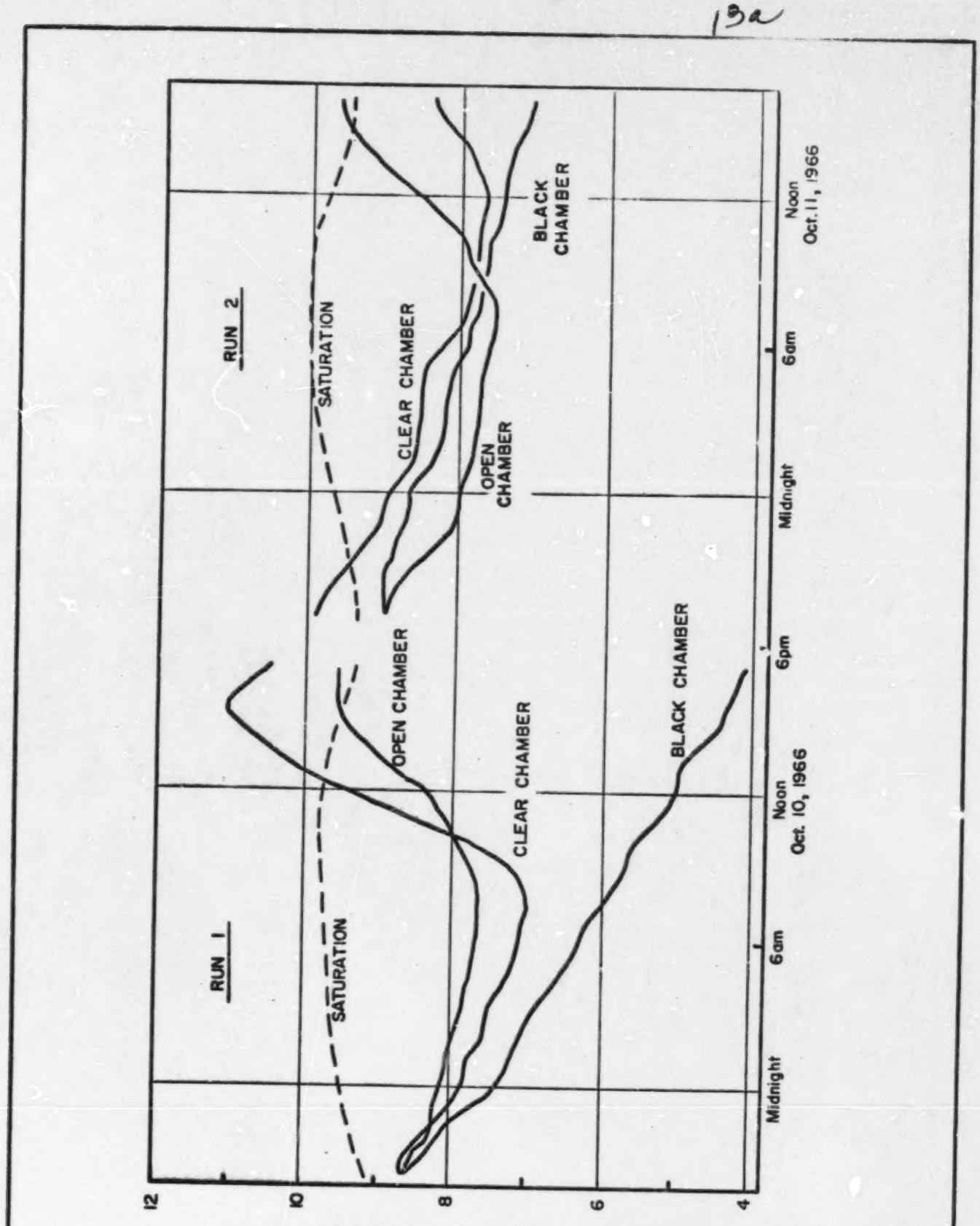
The data presented are primarily for the purpose of illustrating what can be expected from the methods. While the data do not cover a large range of environmental conditions and cannot be used to provide a basis for sweeping conclusions regarding the nature of reaeration, it is possible to point out some of the more prominent characteristics.

As explained earlier, Runs 1 and 2 were made in an area of high velocity where the bottom consisted of unsilted granite. Each run lasted approximately 24 hours and differed in that the chambers were open to the benthos in Run 1 and closed to the benthos in Run 2.

Observed dissolved oxygen concentrations in each chamber, for Runs 1 and 2, indicate that in this particular situation the benthic population plays a predominant role in the stream oxygen balance (Figure 4). In Run 1, it is interesting to note that respiration, as measured in the black chamber, exceeds that of Run 2; and photosynthesis, which is a function of the clear chamber, is reduced because of the elimination of the benthic effect; and diffusion becomes negative upon reaching saturation.

The first portion of Run 3 was conducted under conditions of low light intensity, and the dissolved oxygen concentration did not reach saturation (Figure 5). On the morning of the second day, there was a rapid increase in the dissolved oxygen concentration for the clear chambers. Figure 5 shows that photosynthesis, as reflected in the clear chamber, is greatly reduced during reduced sunlight, and increases rapidly when sunlight increases just before noon on the second day.

In order to separate the components of oxygenation, it is first necessary to convert the dissolved oxygen concentration in each chamber to a weight basis in grams. By then summating



COMPONENTS OF
OXYGENATION IN FLOWING STREAMS
BLUE RIVER – OKLAHOMA

DISSOLVED OXYGEN CONCENTRATION
RUNS 1 & 2

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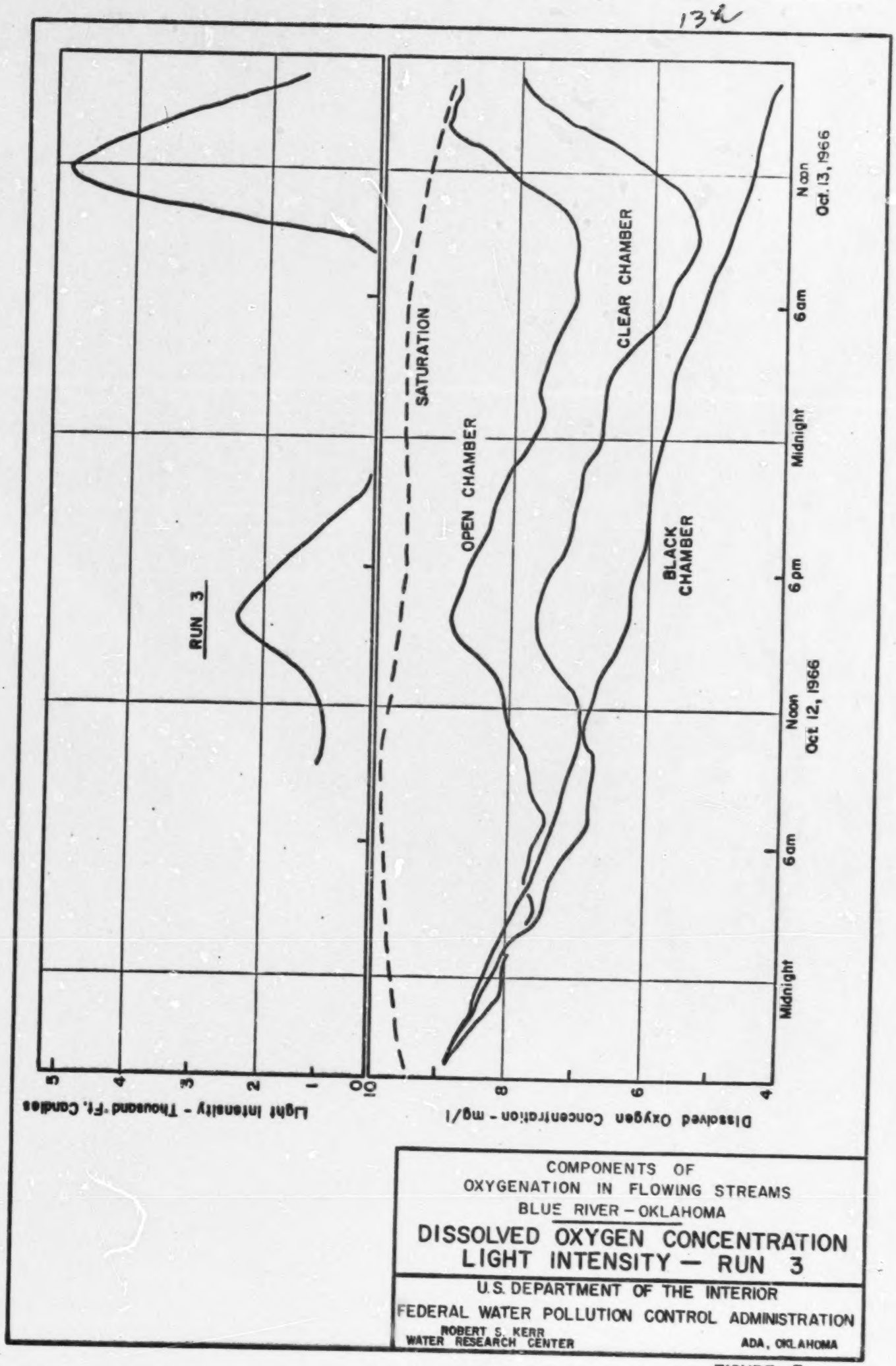
FIGURE 4



COMPONENTS OF
OXYGENATION IN FLOWING STREAMS
BLUE RIVER – OKLAHOMA

DISSOLVED OXYGEN CONCENTRATION
LIGHT INTENSITY — RUN 3

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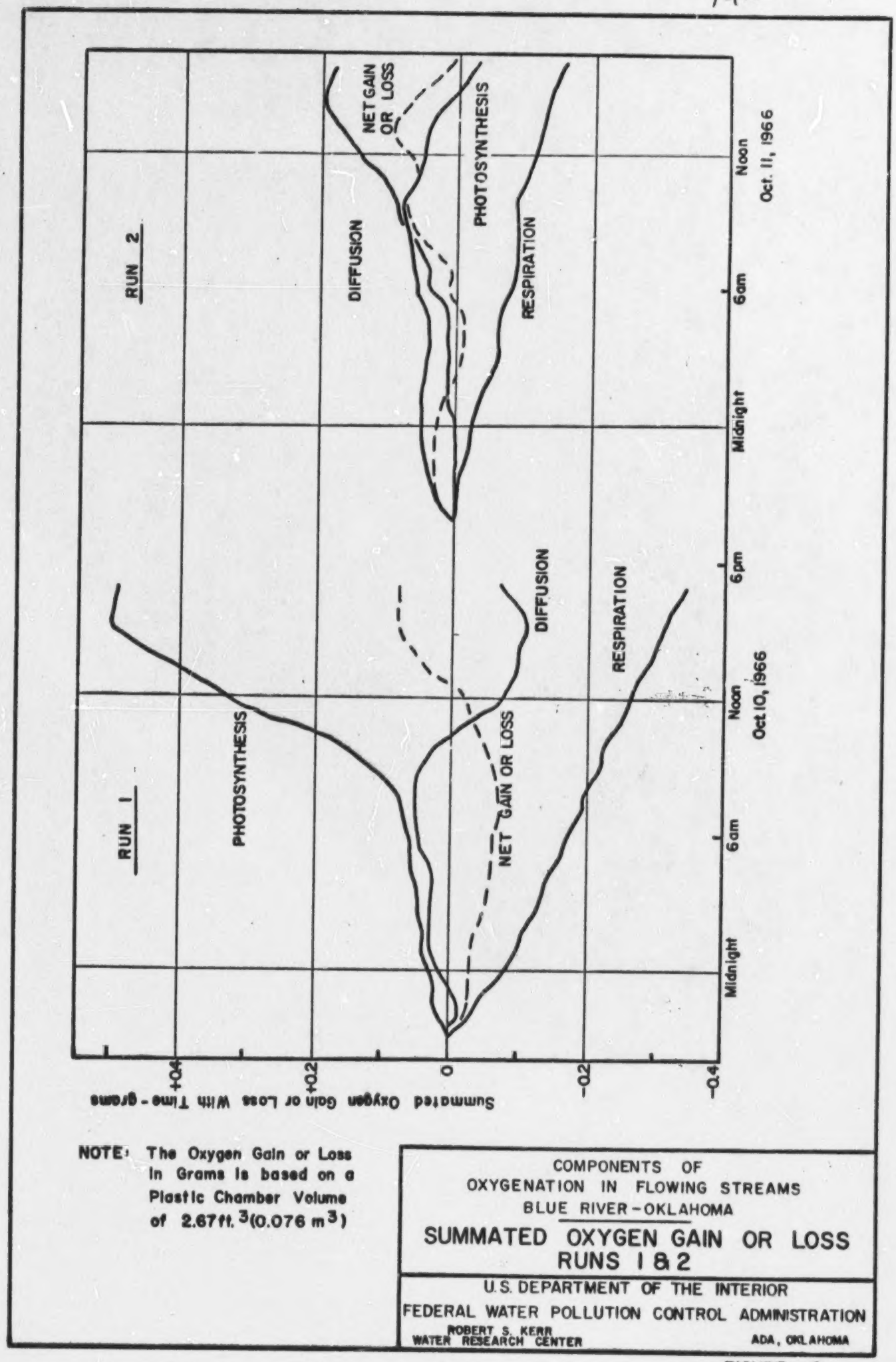
FIGURE 5

the gain or loss in weight of each chamber for incremental times of an hour, each chamber can be compared by reducing the starting point to zero and then comparing rate changes from that point. Further, by subtracting the summated values in the black chamber from those in the clear chamber, the resultant figures represent that oxygen contributed by photosynthesis alone. In a similar manner, the summated oxygen weights in the clear chamber can be subtracted from those in the open chamber leaving a rate change due to diffusion.

In the first run where the benthos was being measured, it can be seen that oxygen supplied by photosynthesis was predominate, and oxygen was lost by diffusion after reaching saturation (Figure 6). In the second run where production by the benthos was negated, diffusion was the primary supplier of oxygen to the system. During Run 3, diffusion was again the major oxygen contributor until the sun appeared on the second day, at which time photosynthesis increased rapidly and diffusion became negative (Figure 7).

It is interesting to note that during Runs 1, 2, and 3, the net oxygen production--either positively or negatively--described by the dashed line returns to zero each day for each run at about the same time of day. Theoretically, the photosynthesis to respiration ratio should be equal to unity. It appears that diffusion only tends to shift the point of equilibrium one way or the other with respect to time.



NOTE: The Oxygen Gain or Loss in Grams is based on a Plastic Chamber Volume of 2.67 ft.^{3} (0.076 m^3)

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BLUE RIVER - OKLAHOMA

SUMMATED OXYGEN GAIN OR LOSS
RUNS 1 & 2

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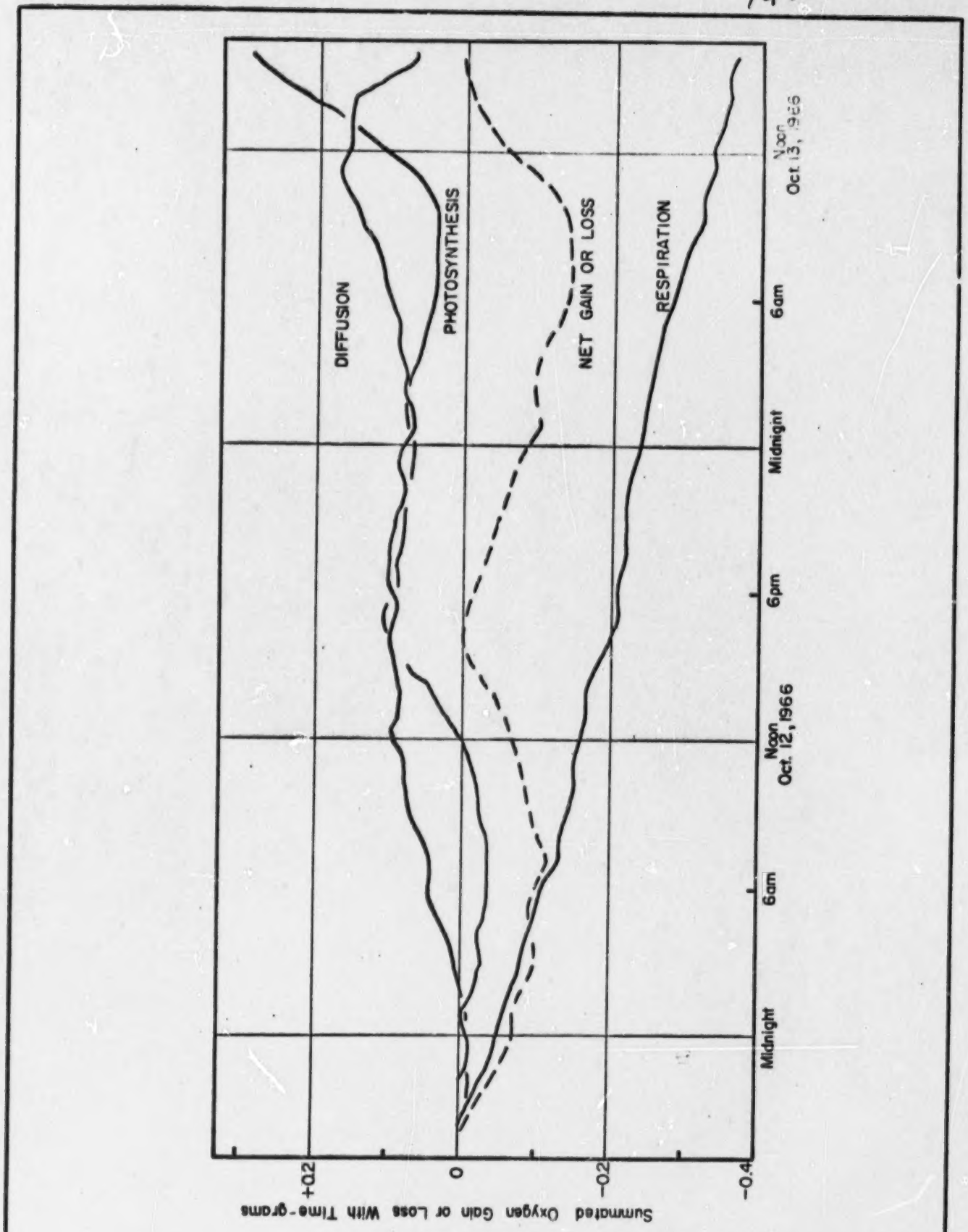
FIGURE 6



NOTE: The Oxygen Gain or Loss in Grams is based on a Plastic Chamber Volume of 2.67 ft.^{3} (0.076 m^3)

COMPONENTS OF
OXYGENATION IN FLOWING STREAMS
BLUE RIVER – OKLAHOMA

SUMMATED OXYGEN GAIN OR LOSS
RUN 3

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FIGURE 7

Total oxygen balance can be made only when that gas which comes out of solution is measured and analyzed. Table 2 presents total volumes of gas produced in the clear chamber over the time period of each run. There was no gas production in the black chamber.

The differences between Runs 1 and 2, as shown in Table 2, indicate that the gases produced are predominately from the benthos.

Table 2

Volume of Gas Liberated from Solution in the Clear Chamber for Each Run

Run Number	Volume of Gas Produced STP (ml)
1	1,747
2	98
3	1,215

Unfortunately, contamination of the pyrogallol absorbent used for determining the oxygen content of the gas prevented a detailed collection of this data, and the only point which is considered accurate is the last measurement of Run 3. This measurement resulted in an oxygen content of 31 percent and amounted to an oxygen weight of 0.54 grams.

Future work will include a complete analysis of the gases produced in order to gain some insight of the biological kinetics involved in the benthos.

DISCUSSION

In order to keep from placing too much responsibility for the criticism of this work on others, a few statements are in order concerning the obvious flaws which might be encountered.

Of course, the most obvious question that may be asked is if the waters held within these chambers do, in fact, behave as if flowing stream conditions were maintained. This question arises from the fact that, even though mixing is provided, natural eddy currents are disrupted and confinement is imposed.

Secondly, an important part of this work is based upon the measurement of respiration. Considerable differences of opinion exist concerning respiration rate and how it is affected by such things as dissolved oxygen concentration and production rate.(7) Admittedly, what is measured here reflects continuous nighttime conditions. The magnitude of this error, if it is an error, is not known.

Although an attempt has been made to provide a current in the open chamber similar to the open stream, currents again are introduced which may affect the extent of exposure of the liquid surface to the atmosphere. Again, the magnitude of error which could be involved here is not known.

The possibility of discharging wastes on an intermittent basis, throughout the day, has been discussed for many years, and the justification for this possibility is evidenced in Figures 6 and 7. The "net gain or loss" curve shown on these

figures, if corrected to represent that oxygen lost to the atmosphere, would provide a basis for the temporal component of a waste release program. This could be done by controlling the oxygen demand rate so that the "net gain or loss" curve would be maintained at the zero level.

As additional information of this kind is collected, it will be possible to represent each component mathematically with appropriate series, the coefficients of which are a function of stream type, location, and geometry. With this model, it will then be possible to optimize the system relative to the oxygenation components and related waste discharges.

It is hoped that this work, which is built on the experience of many other researchers, will take the science closer to obtaining those tools necessary to achieve and maintain clean waters.

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